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Low-Gravity Fluid Physics: A Program Overview

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LOW-GRAVITY FLUID PHYSICS: A PROGRAM OVERVIEW

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To justify the huge sums being spent on these [government funded] projects, proponents inevitably cite the practical spinoffs.... Almost without exception, though, these advances resulted from work done by a few individuals working in relative obscurity - not as the result of a huge Government project. The wellspring of science as well as the practical spinoffs from science is the solitary researcher.

George Chapline, senior physicist with the Lawrence Livermore National Laboratory, in a New York Times editorial, June 28, 1990.

There is an acute need to study the fundamentals of fluid behavior in reduced gravity to provide a data base that can be used in developing the required technologies.

One conclusion from the Microgravity Fluid Management Symposium, held at Lewis Research Center, September 9 to 10, 1986.

INTRODUCTION

The objectives of NASA's microgravity program are (1) to extend our knowledge of the Earth, its space environment, and the universe; (2) to expand the capability for practical applications of space technology; (3) to develop and improve manned and unmanned space vehicles; and (4) to assure continued development of the long-term aeronautics and space research and technology necessary to accomplish national goals. The Office of Space Science and Applications (OSSA) sponsors experimental and theoretical research activities to extend our knowledge of basic and applied phenomena related to fundamental sciences, materials science, and biotechnology. These NASA-funded investigations are conducted by university, industry, and Government researchers using both ground-based facilities, such as drop towers and aircraft, and space-based facilities to obtain a reduced-gravity environment.

One area of research within the broad category of fundamental sciences is fluid dynamics and transport phenomena. Using a low-gravity environment enables a researcher to investigate effects which may be masked in experiments conducted in normal gravity. Gravitationally induced phenomena such as hydrostatic pressure, buoyant convection, sedimentation, and stratification typically inhibit the study of other important processes including surface tension forces, shear forces, interfacial contact angles, and diffusion phenomena. For example, at normal gravity, buoyant convection in most processes may dominate flow driven by surface tension forces or electrical potentials. Also, in normal gravity, the gravitational body force typically dominates the shape, location, and dynamics of a liquid-vapor interface. In reduced gravity, interfacial surface tension forces have an important effect on liquid-vapor interfacial shapes.

The purpose of this document is to provide an overview of the fluids research activity within OSSA's Microgravity Program and to encourage new, worthwhile investigations. NASA's Lewis Research Center presently supports OSSA by providing project management and oversight of OSSA-sponsored activities conducted by universities, industry, and other Government agencies. The fluid physics activities at Lewis can be categorized into five major "theme areas": (1) isothermal/iso-solutal capillary phenomena, (2) capillary phenomena with thermal/solutal gradients, (3) thermal/solutal convection, (4) first- and second-order phase transitions in a static fluid, and (5) multiphase flow.

Within each of these theme areas, there are a number of specific sub-themes. For example, in the area of first- and second-order phase transitions, boiling/condensing and melting/freezing phenomena, as well as critical point phenomena, are included. Appendix A is a summary of proposed research topics for each of the major theme areas. Instead of providing a complete description of all research topics listed in appendix A, this document highlights a few research experiments per theme area, emphasizing those that use either ground-based or space-based low-gravity facilities.

MICROGRAVITY FACILITIES

Ground-Based Facilities

Ground-based and space-based low-gravity facilities have been and will remain an integral part of fluid physics research. This section describes microgravity laboratory facilities that offer the investigator a range of low-gravity durations and acceleration levels.

As shown in figure 1, several facilities provide a free-fall or semi-free-fall condition, where the force of gravity is unopposed. This enables a low-gravity environment for scientific studies. Each facility's capabilities and characteristics must be considered by an investigator in choosing the facility best suited to a particular series of experiments.

To date, most fluid physics studies have taken place in the NASA Lewis Research Center's two drop towers and in its model 25 Learjet. The 2.2-second drop tower, as its name implies, provides 2.2 sec of low-gravity test time for experiment packages with up to 125 kg of hardware mass. A schematic diagram of this drop tower is shown in figure 2(a). Within this building is the drop area, which is 27 m high with a cross section of 1.5 by 2.75 m. The experiment package, an example of which is shown in figure 2(b), is enclosed in a drag shield and then hoisted to the top of the building and suspended there by a highly stressed music wire attached to the release system. A drop begins when a pneumatic system notches the wire, causing it to fail. As the drag shield falls, the experiment package is free to move within it. The only external force acting on the freely falling package is the air drag associated with the relative motion of the experiment package within the drag shield, resulting in an effective gravity level of approximately $10^{-5}g$. Although the low-gravity time is only 2.2 sec, this facility offers both low cost and rapid turnaround time between experiments. It is often used for proof-of-concept or precursor experimentation.

The zero-gravity facility at Lewis, with its 132-m free-fall distance in an evacuated drop chamber, represents a significant expansion in experimental

sophistication and research capabilities over the 2.2-second drop tower. A schematic of this facility is shown in figure 3(a). The zero-gravity facility houses a 6.1-m-diameter, steel-walled vacuum chamber that is 145 m deep. The drop distance of 132 m provides 5.18 sec of free-fall and accelerations of about $10^{-6}g$. Experiments of up to 459 kg are mounted in a 1-m-diameter drop bus (fig. 3(b)). The entire chamber is then evacuated to 0.01 torr. The drop begins when a bolt in the release mechanism is sheared. The bus falls free of drag in the near vacuum and is decelerated in a 6.1-m-deep container of small pellets of expanded polystyrene. Data can be transmitted via telemetry during the drop, allowing the researchers to monitor the progress of the experiment in real time.

Specially modified jet aircraft flying parabolic trajectories can provide longer low-gravity experiment times than drop towers, but with a penalty of higher gravity levels. For an experiment fixed to the body of an aircraft, effective gravity levels only on the order of $10^{-2}g$ can be obtained for up to 20 sec. While aircraft may not offer true microgravity, they do offer the significant advantage of longer duration of low-gravity, and they permit researchers to monitor their experiments in real time, and to reconfigure them between trajectories. The Lewis airborne low-gravity facility, a Learjet model 25, is shown in figure 4(a) together with a flight profile of a low-gravity trajectory. Approximately 1.8 m of cabin length is available for experiment mounting and researcher seating. An example of an experiment installed in the Learjet is given in figure 4(b). Inherent engine lubrication limitations of this aircraft permit a maximum of six trajectories per flight. Intermediate acceleration levels of $1/20$ to $3/4$ of Earth's gravity, including lunar ($1/6g$) and Martian ($1/3g$) levels, can also be achieved in this aircraft.

The Johnson Space Center's KC-135 aircraft operates like the Learjet when flying experiments fixed to the aircraft body, but, because of its size, also permits free-floated experiments with acceleration levels of about $10^{-3}g$ for 5 to 15 sec. In addition, up to 40 trajectories can be performed in a single flight.

Although not used extensively by fluid physics researchers from the United States, sounding rockets can provide a low-gravity environment on the order of $10^{-4}g$ for about 300 sec. Their use should be considered in future experiments that require such a duration and gravity level but do not require direct observation by a researcher.

Space-Based Facilities

Truly long-duration microgravity fluid physics experiments require space-based laboratories such as the U.S. space shuttle. The shuttle flight duration for science missions is typically 7 to 10 days but will soon be extended to up to 16 days. The combined aerodynamic and gravity gradient forces provide a background acceleration level of around $10^{-6}g$. Since crew motion, the most significant disturbance, can induce accelerations in the range of $10^{-3}g$, many investigators request that their experiments be operated during periods of reduced crew activity, when lower gravity levels of at least $10^{-4}g$ can be sustained. Upward and downward data, voice, and video communication links between the crew and the researcher are available. Thermal control, physical space availability, and electrical power and data handling capabilities depend on the experiment location in the shuttle or on the type of mission. These various locations include the shuttle mid-deck, the exposed cargo bay, and the

Spacelab module. Experiments ranging from a mid-deck locker to a get-away-special to a full Spacelab rack can be accommodated.

The future of the fluid physics flight program is one which will take an evolutionary path from today's single-experiment, single-user experiment hardware to modular, multiuser facilities. This concept is shown in figure 5. The next generation of Spacelab hardware will support this evolution by accommodating multiple investigators with similar resource requirements. With the diverse nature of fluid physics, the design of such multiuser hardware will be especially challenging. The goal is twofold. First, by building hardware which can be used by more than one principal investigator, costs can be reduced. Second, considering the limited flight opportunities, multiuser hardware can enable wider flight program participation among potential principal investigators. Careful consideration must be used so that experiments can be designed for the modular, multiuser hardware without affecting the individual experiment's requirements. Use of this Spacelab hardware is planned to continue even after the deployment of the next generation of modular, multiuser facilities aboard the Space Station Freedom.

Eventually to be the cornerstone of the fluid physics in-space program, the fluid physics/dynamics facility on Space Station Freedom is envisioned as two racks (fig. 6): a facility rack and an experiment rack. The facility rack will contain image processors, diagnostics illumination, data acquisition systems, power converters, and other types of hardware which are common to most, if not all, fluids experiments. It will also contain storage space for spare test cells, test fluids, camera lenses, and other ancillary equipment. The facility rack will be designed to remain on Space Station Freedom for 10 to 15 years. The experiment rack will contain equipment which is required by the experiment or class of experiments being run. Some common systems are a fill-and-drain system, a precision temperature control system, and some experiment-specific diagnostic equipment. In the present concept, the experiment rack will be replaced by a new one every 1 to 2 years, and the old rack will be returned to ground-based labs for modifications and upgrades. During the time an experiment rack is being used, experiments which have similar support requirements could be performed by changing the hardware configuration and replacing the test cells and test fluids.

With both Spacelab and Space Station Freedom facilities operational, payload specialists (who may be fluid scientists), together with principal investigators on the ground, should be able to perform a wide variety of experiments. Quite possibly, microgravity fluids experiments will occur daily - an exciting prospect. These complementary facilities should offer investigators a variety of capabilities and provide flight opportunities for the long-term future. This vision will become a reality only with sufficient and dedicated cooperation between NASA, academia, industry, and other Government agencies.

The remainder of this document presents a detailed discussion of a number of experiments in fluid physics, many of which have used or will use the facilities described here. Each major theme area is briefly summarized and then followed by a description of at least one experiment from that theme area.

THEME AREA I - ISOTHERMAL/ISO-SOLUTAL CAPILLARY PHENOMENA

Experiments in this theme area involve isothermal studies of liquid-gas and/or immiscible liquid-liquid interfaces and their interactions with a solid boundary. Key areas of interest include (1) the determination of liquid-gas (liquid-liquid) surface configurations in unique vessel geometries, (2) interfacial stability and dynamics, and (3) contact line stability and dynamics. Experiments are typically conducted under ambient conditions with modular containers, and they require no heating or cooling.

Interfacial Fluid Experiments

In the absence of significant gravitational forces, fluid interface configurations (whether static or dynamic) are largely controlled by the wetting characteristics of the system. On a macroscopic scale these characteristics are commonly described in terms of a contact angle between the fluid phases and a solid bounding surface. Though the behavior of the fluid in the bulk phases (considered as isothermal) are predicted reasonably well by accepted theories, the observed behavior of the fluid at or near the contact line is not well understood. Extended on-orbit low-gravity experiments facilitate the study of contact line dynamics by expanding the region of influence of the fluid boundary into the bulk liquid. Liquid movement and position are determined and/or driven by the phenomena at the contact line. Since such surfaces are common to numerous fluid-interface systems used in space-based applications (fluids management, capillary pumped loops, etc.), it is vital to present and future designs to gather more data through studies in this area.

Figure 7(a) shows the test cell of one study being conducted at Lewis. The simple apparatus consists of a right circular cylinder intersected at its midpoint by a toroid-like bulge, the contour of which is numerically determined. The vessel is rotationally symmetric with the unique property that, for a given fluid volume and contact angle, the bulge portion of the vessel allows a continuum of distinct, symmetric, equilibrium fluid configurations, all having the same mechanical energy. It has been theoretically shown that this family of symmetric solutions is unstable, and that asymmetric deformations yield configurations of lower energy. Subsequently, experimental validation had been suggested in drop tower tests at the Lewis zero-gravity facility. A vessel with this uniquely determined curvature is shown in figures 7(a) and 7(b) with an appropriate liquid fill. Both photos were taken after roughly 5 sec of free-fall. The nonaxisymmetric, low-gravity surface configuration of figure 7(b) is a result of a small disturbance created by tilting the vessel with respect to the gravity vector. Although the vessels were prepared in an identical manner with equivalent liquid fills, the fluid in the disturbed vessel was still moving at the end of the 5.2-sec drop time. Much more microgravity time is needed to observe the desired asymmetric shapes. An experiment similar to the one just described is an approved glovebox experiment which will fly onboard the shuttle on the USML-1 mission scheduled for 1992. The results of this study will provide guidance for developing a universal technique to determine static surface shapes in containers of general cross section and their relative stability. Additional insight will be gained into the nature and magnitude of flow resistance at the contact line, particularly that associated with container geometry. These experiments should determine (1) the limits of the classical theory and (2) the direction of future theoretical studies.

Other drop tower studies that are currently being conducted concern (1) the behavior of liquids on heterogeneous solid surfaces, (2) the stability of the contact line at a discontinuous edge, and (3) the dynamic contact angle effects resulting from large-amplitude surface oscillations. Such studies will result in simpler, more passive designs for fluid systems in low-gravity environments as well as provide a more precise means for predicting system performance.

THEME AREA II - CAPILLARY PHENOMENA WITH THERMAL/SOLUTAL GRADIENTS

Experiments in this theme area study fluid motion resulting when either a liquid-vapor (e.g., bubble) or immiscible liquid-liquid (e.g., droplet) interface experiences a nonuniform temperature and/or concentration field. This motion is due to the dependency of surface tension on temperature/concentration levels. The common factor for these experiments is the crucial role of surface tension as a driver for fluid motion. The following example experiments are described: (1) an immersed bubble-droplet experiment, (2) a surface-tension-driven convection experiment, and (3) a surface-tension-driven instabilities experiment.

Thermocapillary Bubble and Droplet Migration Experiment

Bubbles and droplets in an immiscible liquid under zero gravity will not move because of density differences: another force must move them. Imposing a temperature gradient in the liquid is one way of doing so, as has been demonstrated by theory and normal-gravity experiments. Bubbles and drops tend to move because of the phenomenon of thermocapillarity. Thermocapillarity is where the variation of interfacial tension (due to the temperature gradient) induces a surface flow on the droplet from the hot to the cold side, propelling it to the hot region of the liquid. Studies in thermocapillarity are difficult to perform in normal gravity because of the mitigating effects of buoyancy. In addition, bubble and droplet migration phenomena have several reduced-gravity applications: (1) the removal of dissolved gases that are rejected during solidification and crystal growth, (2) the production of uniformly dispersed composite solids, (3) gas bubble management in liquid rocket fuel and cooling systems, and (4) the design of heat pipes.

The bubble/droplet shape and speed of migration are being investigated by several groups in the U.S and Europe through theoretical and experimental studies. Some previous experiments were performed in space as part of the D1 mission. Several experiments have also been performed in normal gravity, in the Lewis drop tower, and in sounding rockets.

At Lewis, normal-gravity experiments are being conducted for density-matched fluids primarily to obtain clear evidence of thermocapillary migration, to document the flow in the droplets, and to identify candidate fluid pairs for actual microgravity experimentation. One liquid pair that has been used is vegetable oil droplets in silicone oil (5 cS viscosity). They are immiscible and are density-matched at a temperature slightly below room temperature. Temperature gradients (up to 25 °C/cm) are generated in the silicone oil, and vegetable oil droplets of various sizes (up to 1 cm) are added. The droplets move to the hot side beyond the location where the temperature has a value equal to the matched-density temperature (fig. 8). This confirms

that some mechanism, dependent on the imposed temperature gradient, moves the drops to the hot wall. (In the absence of such a mechanism, the drops would not move beyond the location of the density-matched temperature.) Thermocapillarity is precisely such a mechanism. The droplets in these one-g studies, then, are observed to reach a new dynamic equilibrium position in the density-matched system. In the microgravity case, however, the droplets would continue to move toward the hot wall. Direct evidence of thermocapillarity has also been obtained by observing the flow pattern induced within the droplets. A laser light-sheet illumination is used to track aluminum oxide tracer particles added in minute quantities to the droplets. The flow pattern obtained for a 9-mm vegetable oil droplet in a temperature gradient of 6 °C/cm in silicone oil is shown in figure 9. The surface flow is from the hot region (top) to the cold region (bottom), and the return flow within the drop is in the opposite direction. The maximum measured surface velocity was around 140 $\mu\text{m}/\text{sec}$. Flow visualization experiments are currently being performed to compare the thermocapillary flow observed in vegetable oil drops immersed in a water-methanol mixture with that observed in pure methanol drops immersed in silicone oil.

Although such ground-based normal gravity experimental studies demonstrate thermocapillary droplet migration and flow, they cannot fully isolate the phenomenon of thermocapillary migration. Microgravity experiments on bubble and drop migration are therefore necessary. An apparatus termed the bubble, drop, and particle unit is being designed by the European Space Agency to conduct such experiments and is scheduled to fly on the IML-2 Spacelab mission scheduled for January 1993. Experiments are being devised to test current theories on isolated bubble and drop migration and to obtain data on interactions of bubbles and drops among themselves and with neighboring boundaries. A variety of fluid pairs, temperature gradients, and bubble and drop sizes will be used in the experiments.

Surface-Tension-Driven Convection Experiment

Materials processing that involves solidification and crystal growth has demonstrated, on occasion, that dramatic improvements in particular processes can occur in the microgravity environment of space. However, while the effects of natural convection and buoyancy are effectively eliminated in microgravity (possibly the reason for these dramatic improvements), convection currents due to surface tension forces are still present, and can cause deleterious fluid flow oscillations. These types of surface-tension-driven (thermocapillary) flows occur in fluids for which (1) free surfaces exist and (2) components of the temperature gradients are parallel to this interface. These flows will occur no matter how small the driving temperatures are and, in normal gravity, will act in concert with natural convective phenomena. Figure 10 shows normal-gravity flow patterns resulting from the heating of the fluid surface. Extended, on-orbit testing will allow the detailed study of these surface-tension-driven phenomena without the complicating effects of natural convection.

A decade ago scientists discovered that thermocapillary flow in fluids with high Prandtl numbers become oscillatory under certain conditions. (See appendix B for definitions of nondimensional numbers used in this report.) The reason for the phenomenon is still not fully understood today. It is believed that, in addition to the strength of the induced flows, the flexibility of the fluid free surface plays an important role. This hypothesis is

difficult to prove, however, unless tests are conducted over a wide range of Marangoni numbers and surface deformation parameters. Oscillations are currently thought to occur only if the surface deformation parameter exceeds a certain value and if the Marangoni number is within a certain range. Current numerical modeling techniques are not able to predict the parameters for which these oscillations occur because of the inherent coupling between the imposed temperature gradient, the surface flows, and surface deformations. In order to completely understand the physical process and to develop an accurate numerical model, experimental data must be obtained in an extended low-gravity environment.

The surface-tension-driven convection experiment (STDCE) now being built for the USML-1 shuttle mission, scheduled for a 1992 launch, will study surface-tension-driven flows in a cylindrical vessel filled with silicone oil (10 cS viscosity). Two basic heating modes will be studied: (1) a constant-temperature mode, where the surface of a submerged heater and the outer container walls are kept at constant temperatures and (2) a constant-flux mode, where a steady heat flux is applied directly to the free surface (using a CO_2 laser). See figure 11 for an experiment schematic. Variations in temperature gradients, heater power, and free surface shapes will be the major test parameters. The main emphasis of the experiment is to quantify the induced velocity fields and surface temperature distributions (oscillatory flows may occur but are not expected).

Experiments in the Lewis drop tower have been conducted in support of this flight experiment. The aim of these microgravity ground-based experiments was to determine the static and dynamic characteristics of the free-surface shape in an open container. The tests used silicone oil in a 10-cm-diameter Plexiglas container for three different container designs, which were then assessed for their ability to retain the liquid in the container.

Complementary to STDCE, the oscillatory thermocapillary flow glovebox experiment, also scheduled to fly on USML-1 in 1992, is designed to determine the parametric ranges for the transition from steady to oscillatory thermocapillary flow in high Prandtl number fluids. In order to cover a wide range of Marangoni numbers, a variety of container sizes (1- and 3-cm-diam) and silicone oils (2 and 5 cS viscosity) will be used. The fluid will be heated by an electrically conducting wire placed in the test cell which will impose a temperature difference across the liquid free surface. The power to the heater will be slowly increased until the flow becomes oscillatory. Oscillations will be identified by observing the free surface motion, the gross fluid motion, and the internal fluid temperature variations.

Surface-Tension-Driven Instabilities Experiment

The phenomena being studied in the surface-tension-driven convection experiments were a result of the application of temperature gradients parallel to the free surface. If, however, these gradients were perpendicular to this fluid interface, different physics would result. It has been shown in past theoretical and experimental work that, unlike for the case of STDCE, fluid motion may not occur for all cases where perpendicular gradients are applied. For a given fluid, of given thickness, classical theory predicts that fluid

motion will not occur for Marangoni numbers below a critical value. For Marangoni numbers exceeding these critical values, fluid instabilities will result, leading to Benard-type cellular motion.

For many years Benard-type cellular motion was believed to be gravity driven. It is now generally accepted that this type of motion is surface tension driven, although the theoretical basis upon which this assertion is made remains to be experimentally verified. It had been thought that experiments could be conducted in one-g to demonstrate this surface tension dependency by studying very thin fluid layers. This would have significantly reduced the buoyancy contribution. Normal-gravity, thin-film experiments have been conducted and have verified that Benard-type motion occurred only when critical Marangoni numbers were met or exceeded. In addition, results also seem to indicate that secondary, "subcritical" fluid motion took place at Marangoni numbers well below the classical values. Moreover, the thinner the fluid layers, the earlier (lower Marangoni numbers) this secondary motion would occur.

If these low-Marangoni-number, low-Rayleigh-number experiments were conducted in low gravity, thicker fluid layers could be used to facilitate data gathering, and the study of secondary flows would be enhanced. The determination of critical Marangoni numbers for these secondary flow instabilities could also be made. A space experiment would also provide irrefutable evidence that these types of instabilities are surface tension driven.

THEME AREA III - THERMAL/SOLUTAL CONVECTION

Experiments in this theme area study density-driven convection in enclosures. There are no free surfaces and, therefore, no surface-tension-driven convection. Although no particular flight experiment at Lewis is under development in this theme area, some previous normal-gravity and numerical modeling work at Lewis is described. Unlike most other experiments described in this document, the thermal/solutal convection experiments are uniquely characterized by the absence of a free interface and a stronger dependence on the direction of the gravity vector, even at very low gravity.

Thermal/Solutal Convection Experiments

Thermal/solutal convection experiments are characterized by the convective flow behavior in enclosed fluids (no free surface) due to density gradients. The density gradients could be thermally established, solutally established, or the combined mechanism of these two (double diffusive or thermal/solutal convection).

In potential thermal/solutal convection experiments, some of the key governing nondimensional parameters are the thermal and solutal Rayleigh numbers. These parameters decrease with the gravity level. Cases of low Rayleigh numbers can, of course, be studied on the ground; but because both the thermal diffusivity and kinematic viscosity are very small, the low-Rayleigh-number, normal-gravity condition can be realized only by having relatively small temperature and concentration gradients. As a result, coverage for parameter ranges of practical interest would not be provided, and very high resolution requirements would be imposed on the temperature/concentration

measurement instrumentation. In microgravity environments, such restrictions can be relaxed, and low-Rayleigh-number cases over a wider range of conditions can be studied.

Experiments in this theme area measure the relevant temperature, velocity, and concentration distributions as well as document the resulting flow patterns. A potential experiment may use a variety of low- to high-Prandtl-number fluids (thermal convection experiments) and electrolytic fluids such as copper sulfate to introduce concentration gradients for the thermal/solutal studies. Experiments could study a variety of enclosure sizes and aspect ratios and would require knowledge of (if not control of) the direction of the g-vector.

To better understand the underlying physics and to better execute and design potential experiments, numerical simulation can be especially effective. It is questionable, however, whether current numerical techniques and computer hardware capabilities will be able to resolve the more complex flow structure of double diffusive convection - all the more reason for performing microgravity experiments. The experimental data obtained under microgravity can also be used to guide the numerical studies for these more complex flow structures and to identify the range of applicability of numerical simulations. Figure 12 represents some of the previous studies at Lewis and compares some experimental and computed flow patterns for an enclosure subject to thermal convection in normal gravity. Good qualitative agreement is shown. Figure 13 shows the more complex flow patterns resulting from thermal/solutal convection in normal gravity. Not only were various convecting fluid layers established in these double diffusive cases, more complex secondary flow patterns such as "fingering" were also observed. In low gravity these secondary flows should be easier to observe, since the boundary layers would be larger.

THEME AREA IV - FIRST- AND SECOND-ORDER PHASE TRANSITIONS IN A STATIC FLUID

Experiments in this theme area involve either first- or second-order phase-change phenomena. First-order phase change experiments will further the study of either liquid-vapor or liquid-solid phase-change phenomena. To distinguish experiments in this category from those in multiphase flow with heat transfer, no forced external convective flow is assumed: the area of interest is the phase-change mechanism itself. An experiment studying liquid/vapor phase-change phenomena (pool boiling experiment) is described. Another Lewis experiment being conducted but not described here is a Learjet experiment studying the melting-freezing transition of aluminum undergoing solidification in low gravity.

Investigations of second-order phase transitions are currently focused on near-ambient-temperature critical point phenomena. The goal here is to better determine the fluid physics in the phase transition regimes near the critical point. A critical fluid equilibration experiment is described.

Nucleate Pool Boiling Experiment

An improved fundamental understanding of nucleate pool boiling heat transfer will be useful in several space-related technologies, including

(1) long-term storage of cryogenic fluids (storage vessel venting and cool-down), (2) temperature control of high-power electronics, and (3) wickless heat pipes. Nucleate pool boiling is a complex, dynamic, and locally transient process. This is especially true in low gravity. Important pool boiling mechanisms include (1) bubble nucleation, (2) dynamic bubble growth and subsequent motion, and (3) the effect of specific systems properties on bubble departure (properties such as surface tension, momentum, buoyancy, and viscosity, among others). The study of pool boiling in microgravity permits observation of transient bubble nucleation without (1) convective disturbances introduced by buoyancy and (2) the buoyant effects on the bubbles themselves. Microgravity also provides the well-defined initial temperature conditions necessary for analytical computer simulations that predict nucleation and bubble behavior.

Pool boiling tests have been conducted in the Lewis zero-gravity facility to provide support for a planned shuttle experiment. The experimental hardware used to conduct these tests is shown in figure 3(b). The drop tests began by locally heating the liquid in microgravity, thereby reducing the convective disturbances that would have been generated if such heating was initiated in normal gravity. Therefore, liquid temperature distributions developed by heat conduction only. The delay time from initiation of heating to nucleation was determined and used to guide the selection of the appropriate heat flux values and time requirements for the shuttle experiment.

The hardware designs for the shuttle and zero-gravity facility apparatuses are very similar. The test fluid in either case is the fluorocarbon R-113. This is an inert, nonconducting fluid with a boiling point of 47 °C at atmospheric pressure. The heater is a transparent gold film on quartz. With this transparent film, the vapor bubble formation and growth can be viewed and filmed simultaneously from the side and from beneath the heating surface (fig. 14). Pressure control is used to produce various thermodynamic states of bulk liquid subcooling and is maintained by a bellows between the R-113 test vessel and nitrogen chamber. Pressures are recorded together with various temperature measurements near the heating surface, in the bulk fluid, and in the quartz substrate. The tests at the zero-gravity facility were conducted for a variety of subcoolings (maximum change in temperature, 11 °C) and heater fluxes (8 W/cm² maximum). The flight experiment will consist of nine tests, with heat flux and liquid subcooling as the independent parameters.

The pool boiling experiment (PBE) is scheduled to be flown on the shuttle as a get-away-special in the early 1990's. The basic configuration is illustrated in figure 14. Observation of long-term vapor dynamic behavior following transient bubble growth is one important area of study. Other results of the flight experiment are expected to be (1) the relation of the observed liquid-vapor behavior to heat flux, initial subcooling, and heater surface temperature variations, (2) the comparison of computed vapor bubble growth rates versus observed values, and (3) the correlation of nucleation delay time to theory.

Critical Fluid Thermal Equilibration Experiment

Any pure fluid possesses a liquid-vapor critical point. It is uniquely defined by a temperature, pressure, and density thermodynamic state. For states with either temperature, pressure, or density greater than the critical values, liquid and vapor are no longer distinguishable. At the critical

point, the fluid experiences large density fluctuations and long-range correlations. A consequence is that the fluid is singularly compressible.

Compressibility is the root of the troubles caused by gravity. On average, a constant-volume fluid at its critical density cannot maintain a large portion of itself at the critical point; the weight of the fluid is enough to compress a portion of the sample to a density above the critical density, leaving the other portion below the critical density. There then remains only a thin layer between the two portions at the critical density. The closer to the critical temperature, the more compressible the fluid, and the thinner the critical zone. At some temperatures the zone is too small to measure thermodynamic properties. Low gravity reduces the weight of the fluid on itself and widens the critical zone for a given temperature, and allows one to go closer to the critical temperature before experimental probe limits are reached. Another key fact about near-critical fluids is that the time it takes for a sample to reach thermal equilibrium approaches infinity as the critical point is approached. This necessitates long-duration testing, which can be troublesome for space experiments. Subsequently, the uncertainty in the appropriate time scales has spawned significant scientific interest.

A space experiment being developed at Lewis to address the thermal equilibration-time issue involves a small, constant-volume sample of sulfur-hexafluoride thermostated with milli-Kelvin control near its critical temperature of 45.54 °C. Observations will then be made using interferometry, visualization, and light transmission techniques. The fundamental objectives of this critical fluid thermal equilibration experiment (CFTE) are (1) to observe large-phase domain homogenization with and without stirring, (2) to observe time evolution of heat and mass after a temperature step is applied to a one-phase equilibrium sample, (3) to observe phase evolution and configuration upon traversing to two-phase from one-phase equilibrium, and (4) to study the effects of stirring on a low-gravity two-phase configuration. Other objectives include studying two-phase to one-phase heating dynamics (starting from a two-phase low-gravity configuration) and quantifying the mass and thermal homogenization time constant of a one-phase system under logarithmic temperature steps. This shuttle experiment is manifested to fly in December 1990 on IML-1. Two equivalent sample cells (fig. 15) will be integrated into the European Space Agency (ESA) critical point facility.

THEME AREA V - MULTIPHASE FLOW

Experiments in this theme area involve convective multiphase fluid flow with and without heat transfer. The "fluids" involved could, in principle, be liquid-vapor, liquid-gas, immiscible liquid-liquid pairs, or even liquid-solids. In the adiabatic case (no heat transfer), flow patterns, phase distributions, and pressure drop characteristics are of primary importance. For nonadiabatic cases, heat and mass transfer characteristics are important as well. In addition to these macroscopic phenomena, thin-film behavior, bubble distribution, and liquid front behavior during boiling/condensation are also areas of interest. Two adiabatic two-phase flow experiments will be highlighted here: an air-water Learjet effort and an air-water flowthrough-fittings experiment designed for the 2.2-second drop tower.

Multiphase Flow Experiments

Experiments on two-phase flow systems in a low-gravity environment can reveal the effect of different mechanisms normally masked by gravitational effects. For example, phase stratification for two-phase systems (sedimentation for the cases involving solids) is a manifestation of gravity-induced density differences. Other manifestations of gravity include buoyancy driven flows. An example of this includes oscillating liquid films for the case of gas-liquid vertical upward flow. In a low-gravity environment, these density-driven phenomena (sedimentation and oscillating flow) would be significantly reduced. Surface tension/shear force effects would then become more dominant and could be measured readily, especially in systems with larger diameters.

Key research areas for two-phase flow systems include developing an understanding of interfacial phenomena (e.g., capillary waves and entrainment) and predicting the interaction between the mixture and the flow channel. Interfacial heat and mass transfer is also important for systems when either melting, boiling, condensing, or solidification occurs. The pressure gradient and oscillatory effects are other key research areas aimed at providing design information for space-based systems. Space applications include fluidized bed reactors (relevant to space-based power systems), space propulsion systems, fluid management systems, thermal management systems, and environmental control/life support systems (ECLSS). Gas-liquid two-phase flow is a cornucopia of different fluid phenomena, such as bubble growth/coalescence, droplet formation, interfacial shear, wave shape/velocity, phase distribution, and rewetting. Characteristics of these phenomena, which have significant impact on engineering designs, are incorporated into modeling schemes to predict parameters such as pressure drop and heat transfer coefficients.

Two separate in-house experimental programs are being conducted at NASA Lewis. The first effort is focused on gas-liquid two-phase flow through straight conduits. The second effort is examining the effect that changes in conduit geometry (such as contractions, expansions, and bends) have on gas-liquid flow characteristics. Figure 16 shows the Lewis apparatus used to conduct experiments aboard the Lewis Learjet. This rig can provide gas superficial velocities from 0.1 to 20 m/sec and liquid superficial velocities from 0.1 to 1.1 m/sec for a 1.27-cm-i.d. test section. Test durations are limited to 20 sec, and a maximum of four tests per flight can be performed. Instrumentation includes high-speed movie cameras (capable of framings rates of 400 frames/sec), data acquisition systems (capable of recording pressures, temperatures, and flowrates), and materials such as Plexiglas for the test sections.

Tests conducted to date have used the following liquids: water, a water-surfactant mixture, and a water-glycerine mixture. Tests have been conducted over a range of air and liquid flowrates for lunar ($\sim 0.17g$) and low-gravity ($< 0.01g$) environments. Measurements include void fraction, film thickness, Taylor bubble length, slugging frequency, pressure drop, and flowrates. The study of two-phase flow through a straight conduit has identified three flow regimes: bubbly, slug, and annular. Slug flow is illustrated in figure 17. These flow regimes or flow patterns are functions of the gas and liquid properties, the flowrates of each phase, the tube diameter, and the magnitude and direction of the gravity vector.

The drop tower apparatus shown in figure 2(b) is used to study two-phase flow through changes in conduit geometry. This rig is more limited with respect to its flow rate capabilities: it can provide gas superficial velocities from 0.3 to 1.1 m/sec and liquid superficial velocities from 0.5 to 1.0 m/sec for a 0.95-cm-i.d. tube. Test durations can be up to 6 sec, with 2 sec for "pre-drop" data, 2.2 sec for low gravity data, and the remainder for "post-impact" data.

The study of two-phase flow through changes in conduit geometry has focused on contractions and expansions. Tests have been conducted using the drop tower rig for 0.95 to 0.63 cm contraction and 0.95 to 2.54 cm expansion. An example of a Taylor bubble entering a contraction is shown in figure 18. Plans call for another drop tower rig to be built that would have a wider range of flowrate capabilities and a vertical test section.

FINAL THOUGHTS

Numerous fluid physics experiments have been discussed, ranging from the relatively simple liquid-vapor interfacial configuration experiment to the more complex two-phase flow experiment. The brief sampling of experiments described in this document were organized under five theme areas to categorize, to some extent, the work being done at Lewis for the Office of Space Science and Applications (OSSA). These theme areas include (1) isothermal/iso-solutal capillary phenomena (2) capillary phenomena with thermal/solutal gradients (3) thermal/solutal convection (4) first- and second-order phase transitions in a static fluid, and (5) multiphase flow. It should be recognized, however, that many significant areas of fluid physics have not been included in this overview. Some of these areas include diffusion and solidification/melting phenomena. The true breadth of fluid physics becomes apparent when it is realized that fluid processes also play an important role in other disciplines as well (e.g., material sciences, biology, and combustion sciences).

The goal of conducting fluid physics research in a low-gravity environment is to increase the understanding of the fundamental processes taking place. Many of the basic questions about fluid physics can be fully addressed only in a microgravity environment. Although the knowledge gained is reason enough to conduct ground-based and on-orbit reduced-gravity experiments, the real payoff is that basic research supports the design and development of such space systems as power, thermal control, and life support systems. Since it underpins many of the technological areas that are and will be key to many of NASA's programs, fluid physics will continue to be an important and relevant area of research for many years to come.

Only when fundamental processes are thoroughly understood can space systems be designed with confidence and efficiency. Furthermore, it is from performing basic research that innovative approaches to solving technological problems can be found.

Research must be pursued on a broad front, to identify and quantify technical possibilities before their usefulness can be judged. Such a research and technology program is therefore properly conceived as opportunity generating, not directed toward applications.

Pioneering the Space Frontier, 1986, as referenced in Leadership and America's Future in Space, a report to the Administrator by Dr. Sally K. Ride, August 1987.

PROGRAM PARTICIPATION

NASA provides financial and facility support, typically for a three year "definition study" period, to academic and industrial principal investigators. Their initial proposals and subsequent progress are evaluated via the peer review process, which addresses the following types of questions:

- Is there a clear need for microgravity experimentation, particularly space-based experimentation?
- Is the effort likely to result in a significant advance to the state of understanding?
- Is the scientific problem being examined of sufficient intrinsic interest or practical application?
- Is the conceptual design and technology required to conduct the experiment sufficiently developed to ensure a high probability of success?

Principal investigators collaborate with a NASA technical monitor to conduct the necessary research to answer these questions. Precursor experimental studies conducted in the drop towers and in aircraft will provide data and confirm concepts during this definition study period.

If it is believed that spaceflight experiments are needed, the principal investigators then present their results to a NASA-sponsored review panel composed of their scientific and engineering peers. If the review panel recommends continuing to a space flight experiment, NASA assigns a team of engineers and scientists to the multi-year development of space flight hardware that meets the principal investigators' specifications. NASA continues project support by conducting additional research, consulting with the principal investigators, and providing design and safety reviews before spaceflight. The principal investigator then monitors the experiment in flight and subsequently analyzes and publishes the data.

These procedures are typical for space-based experiments; however, NASA also supports complementary research. More information about the details of the process of proposal submission, progress reviews, and space flight project selection is available by writing to the Microgravity Fluids Branch, MS 500-217, NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 44135.

The following people, listed alphabetically, contributed to the writing or the editing of this report: R. Balasubramaniam, Fran Chiaramonte, J.C. Duh, Myron Hill, John McQuillen, Terry O'Malley, Howard Ross, Robert Salvino, Jack Salzman, Robert Thompson, Richard Vernon, Mark Weislogel, and Allen Wilkinson.

APPENDIX A

SUMMARY OF POTENTIAL EXPERIMENTS FOR THE DIFFERENT THEME AREAS

Theme Area I

Experiments in this theme study liquid/vapor/gas interactions in an isothermal environment. Immiscible liquid/liquid interactions also enter into this area. There are no significant density-driven nor surface-tension-driven flows. The experiments will focus on (1) static and dynamic behavior of phase boundaries (liquid/gas or liquid/liquid), (2) stability of phase boundaries, and (3) static and dynamic behavior of container/phase boundaries. This latter point addresses fluid-container intersection physics such as contact line behaviors.

Potential experiments include

(1) Free surface statics, the study of capillary dominated liquid/vapor interfacial configurations in various vessels.

(2) Free surface dynamics, the study of liquid/vapor interfacial dynamics and stability in various vessels resulting from forced oscillations.

(3) Contact line movement, the study of liquid/vapor contact line movement along a solid surface (e.g., flow in a tube).

Theme Area II

Experiments in this theme area study phenomena which result when a liquid/vapor interface is exposed to a nonuniform temperature (or concentration) field. The resulting temperature (concentration) gradients cause thermocapillary (or solutal) fluid motion. There are no significant density-driven flows. There are two basic configurations of experiments: (1) one of the phases is completely immersed in the other and (2) the phase boundary intersects the container itself. In the latter case the orientation of the gradient vector with the interface is also important in determining the type of physics studied (e.g., gradients parallel or perpendicular to the phase interfaces).

Potential experiments include

(1) Bubble/droplet dynamics, the study of bubble rise behavior in various liquids. Terminal velocity and exterior temperature and velocity fields are also areas of interest.

(2) Surface-tension-driven convection. Temperature (or concentration) gradients are parallel to fluid/vapor interface and Marangoni convection results. Of particular interest are velocity distributions, temperature distributions, and flow oscillations.

(3) Surface-tension-induced instabilities. Temperature gradients are perpendicular to fluid/vapor interfaces. Critical Marangoni number at the onset of cellular convection is a key area of study.

Theme Area III

Experiments in this theme area are characterized by density-driven, rather than surface-tension-driven flows. There are no phase interfaces involved. Flows are induced by imposed thermal and/or concentration gradients. Velocity and temperature fields are the main parameters of interest. These experiments are also characterized by the particular requirement of precisely knowing the gravity vector direction.

Potential experiments include

(1) Thermal or solutal convection, the study of density-driven thermal (or solutal) convection in a low-gravity environment. Numerical models may adequately predict low-gravity performance.

(2) Thermal/solutal (double diffusive) convection, the study of the combined effects of thermal and solutal convection. Simultaneous thermal and solutal driving mechanisms occur, resulting in more complex flow patterns.

Theme Area IV

Experiments in the area of first-order phase change will study phenomena occurring during liquid/vapor or liquid/solid phase change transitions. There are no externally imposed convective flows for experiments in this area. Experiments will consider the type of transition as well as the direction of heat flow (boiling/condensing, melting/freezing). The rate of heat transfer across the interface is also important, since this could determine, for instance, whether evaporation or boiling processes occur.

Potential experiments include

(1) Evaporation/pool boiling (liquid/vapor), the study of phenomena which result from the liquid-to-vapor phase transition.

(2) Film/droplet condensation (liquid/vapor), the inverse process to pool boiling.

(3) Melting/freezing interfacial dynamics (liquid/solid), which overlaps with the materials discipline. The main interest is in the fluid physics aspects only and how they may affect solidification processes.

Theme Area V

Experiments in this theme area all involve convective flow, with and without heat transfer. The flow could consist of either liquid/gas, liquid/vapor, immiscible liquid/liquid or liquid/solid combinations. In addition, there are some situations (with heat transfer) whereby one would experience three-phase flow. The main areas of interest for the adiabatic case are flow patterns, phase distributions, and pressure drop characteristics. For cases with heat transfer, heat transfer coefficients and phase change phenomena are also important.

Potential experiments include

(1) Adiabatic flow, the study of flow patterns and pressure drop characteristics of coflowing immiscible liquid and gas phases. Detailed physics of the three major flow regimes are of interest. These include bubble distribution and coalescence (bubbly flow); slugging frequencies and Taylor bubble shapes (slug flow); and film thicknesses and entrainment phenomena (annular flow).

(2) Flow boiling, the study of single-component flow boiling. All regimes from subcooled nucleate to film and mist regimes should be addressed. Heat transfer (as well as pressure drop) characteristics are important.

(3) Film condensation, the study of single-component convective condensation. Film and drop condensation should both be included. Again, a full range of qualities should be covered.

APPENDIX B

DEFINITION OF NONDIMENSIONAL NUMBERS

Prandtl Number (Pr)

The Prandtl number is important in fluid flow situations where momentum and energy transport are occurring. It is defined as

$$Pr = \frac{\mu C_p}{k}$$

where

μ absolute viscosity, gm/cm-sec
 C_p constant pressure specific heat, cal/gm-°C
 k thermal conductivity, cal/cm-sec-°C

Marangoni Number (Ma)

The Marangoni number is important in processes involving thermocapillarity. These are typically driven by imposed temperature gradients. It is defined as

$$Ma = \frac{(-d\sigma/dT)(dT/dz)L^2}{\mu\alpha}$$

where

σ surface tension between two immiscible fluids, dynes
 T temperature, °C
 $d\sigma/dT$ change in surface tension with respect to changes in temperature, dynes/°C
 dT/dz temperature gradient, °C/cm
 L appropriate reference length, cm
 α thermal diffusivity ($k/\rho C_p$), cm²/sec
 ρ density, gm/cm³

Rayleigh Number (Ra)

The Rayleigh number is important in density-driven fluid flows. The flows could be either thermally or solutally driven (thereby producing a thermally or solutally derived Ra number). It is defined as

$$Ra = \frac{g\beta \Delta T L^3}{\nu\alpha}$$

where

g gravity level, cm/sec²
 β coefficient of thermal expansion, °C⁻¹
 ΔT temperature differences between hot and cold surfaces, °C
 ν kinematic viscosity (μ/ρ), cm²/sec

SELECTED BIBLIOGRAPHY

Abramson, H.N.: The Dynamic Behavior of Liquids in Moving Containers. NASA SP-106, 1966.

Balasubramaniam, R.; and Lavery, J.E.: Numerical Simulation of Thermocapillary Bubble Migration Under Microgravity for Large Reynolds and Marangoni Numbers. Numer. Heat Trans. Pt. A Appl., vol. 16, no. 2, Sept. 1989, pp. 175-187.

Boukari, H., et al.: Critical Speeding Up in Pure Fluids. Phys. Rev. A, vol. 41, no. 4, Feb. 1990, pp. 2260-2263.

Concus, P.; and Finn, R.: Capillary Surfaces in Microgravity. To appear in AIAA review volume Progress in Low-Gravity Fluid Dynamics and Transport Phenomena, J. Koster and R.L. Sani, eds., 1990.

Cooper, M.G.: Effects of Orientation in Nucleate Pool Boiling. Collected Papers in Heat Transfer, Vol. 2, K.T. Yang, ed., ASME, 1988, pp. 165-168.

Dhir, V.K.; and Tung, V.X.: A Thermal Model for Fully Developed Nucleate Boiling of Saturated Liquids. Collected Papers in Heat Transfer, Vol. 2, K.T. Yang, ed., ASME, 1988, pp. 153-164.

Dix, D.; Orozco, J.; and Francisco, H.: An Experimental Study in Nucleate Pool Boiling. Collected Papers in Heat Transfer, Vol. 2, K.T. Yang, ed., ASME, 1988, pp. 187-192.

Duh, J.C.: Numerical Modeling of Enclosure Convection. IAF Paper 89-403, Oct. 1989.

Dukler, A. E., et al.: Gas-Liquid Flow at Microgravity Conditions: Flow Patterns and Their Transitions. Int. J. Multiphase Flow, vol. 14, no. 4, 1988, pp. 389-400.

Janicot, A.: Experimental and Theoretical Studies of Gas-Liquid Two-Phase Flow at Reduced Gravity Conditions. Master's Thesis, Univ. of Houston, 1988.

Kamotani, Y.; and Ostrach, S.: Design of a Thermocapillary Flow Experiment in Reduced Gravity. J. Thermophys. Heat Trans., vol. 1, no. 1, Jan. 1987, pp. 83-89.

Kamotani, Y., et al.: Experimental Study of Natural Convection in Shallow Enclosures with Horizontal Temperature and Concentration Gradients. Int. J. Heat Mass Trans., vol. 28, no. 1, Jan. 1985, pp. 165-173.

Keshock, E.G.; and Siegel, R.: Forces Acting on Bubbles in Nucleate Boiling Under Normal and Reduced Gravity Conditions. NASA TN-D-2299, 1964.

Lekan, J.: Microgravity Research in NASA Ground-Based Facilities. AIAA Paper 89-0236, Jan. 1989. (Also, NASA TM-101397.)

Merte, H., Jr.: Combined Roles of Buoyancy and Orientation in Nucleate Pool Boiling. Collected Papers in Heat Transfer, Vol. 2, K.T. Yang, ed., ASME HTD-VOL. 104, ASME, 1988, pp. 179-186.

Moldover, M.R., et al.: Gravity Effects in Fluids Near the Gas-Liquid Critical Point. Rev. Mod. Phys., vol. 51, no. 1, Jan. 1979, pp. 79-99.

Narain, A.; and Kizilyalli, Y.: Pure Driven Flow of Pure Vapor Undergoing Laminar Film Condensation Between Parallel Plates. Accepted for publication in International Journal of Non-Linear Mechanics, vol. 25, 1990.

Oker, E.; and Merte, H., Jr.: Transient Boiling Heat Transfer in Saturated Liquid Nitrogen and F113 at Standard and Zero Gravity. (REPT-074610-52-F, University of Michigan; NASA Contract NAS8-20228), NASA CR-120202, 1973.

Onuki, A.; Hao, H.; and Ferrell, R.: Fast Adiabatic Equilibration in a Single-Component Fluid Near the Liquid-Vapor Critical Point. Phys. Rev. A, vol. 41, no. 4, Feb. 1990, pp. 2256-2259.

Ostrach, S.: Natural Convection Heat Transfer in Cavities and Cells. Heat Transfer 1982, Vol. 1, U. Grigull et al., eds., Hemisphere Publishing Co., 1982, pp. 365-379.

Pline, A.D.; and Jacobson, T.P.: Containment of a Silicone Fluid Free Surface in Reduced Gravity Using Barrier Coatings. NASA TM-101314, 1988.

Pline, A.D., et al.: Hardware Development for the Surface Tension Driven Convection Experiment Aboard USML-1 Spacelab Mission. AIAA Paper 89-0406, Jan. 1989. (Also, NASA TM-101404.)

Rashidnia, N.; and Balasubramaniam, R.: Thermocapillary Migration of Liquid Droplets in a Temperature Gradient in a Density Matched System. NASA CR-185178, 1989.

Rohsenow, W.M.: What We Don't Know and Do Know About Nucleate Pool Boiling Heat Transfer. Collected Papers in Heat Transfer, Vol. 2, K.T. Yang, ed., ASME, 1988, pp. 169-172.

Salzman, J.A.; and Masica, W.J.: Lateral Sloshing in Cylinders Under Low-Gravity Conditions. NASA TN D-5058, 1969.

Schwartz, S.H.: Saturated Pool Boiling of Water in a Reduced Gravity Environment. PhD. Dissertation, University of Southern California, Los Angeles, 1966.

Seebold, J.G.; Hollister, M.P.; and Satterlee, H.M.: Capillary Hydrostatics in Annular Tanks. J. Spacecraft Rockets, vol. 4, no. 1, Jan. 1967, pp. 101-105.

Space Experiments Division/Microgravity Combustion Branch, Microgravity Combustion Science: A Program Overview. NASA TM-101424, 1989.

Space Experiments Division/Microgravity Fluids Branch, Conceptual Design for the Space Station Freedom FP/DF, presented at the FP/DF Assessment Workshop, Cleveland, OH, Jan. 24-25, 1990.

Subramanian, R.S.: The Motion of Bubbles and Drops in Reduced Gravity. Transport Processes in Bubbles, Drops and Particles, R.P. Chhabra and D. DeKee, eds., Hemisphere Publishing Corp., New York, 1990 (to be published).

Tong, W.; Simon, T.W.; and Bar-Cohen, A.: A Bubble Sweeping Heat Transfer Mechanism for Low Flux Boiling on Downward-Facing Inclined Surfaces. Collected Papers in Heat Transfer, Vol. 2, K.T. Yang, ed., ASME, 1988, pp. 173-178.

Wilkinson, R.A.: Critical Phenomena in Microgravity Environments. Bull. Am. Phys. Soc., vol. 34, no. 718, 1989, p. 718.

Wozniak, G.; Siekmann, J.; and Srulijes, J.: Thermocapillary Bubble and Drop Dynamics Under Reduced Gravity - Survey and Prospects. Z. Flugwiss. Weltraumforsch., vol. 12, no. 3, May-June 1988, pp. 137-144.

Zappoli, B., et al.: Anomalous Heat Transport by the Piston Effect in Supercritical Fluids Under Zero Gravity. Phys. Rev. A, vol. 41, no. 4, Feb. 1990, pp. 2264-2267.

Zell, M.; and Straub, J.: Experimental Investigation of Boiling Phenomena Under Microgravity Conditions. Presented at ASME/JSME Thermal Engineering Conf., Honolulu, HA, Mar. 1987.

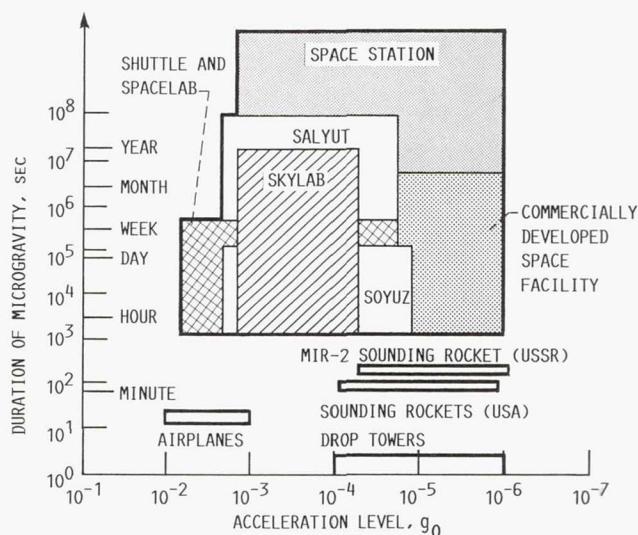
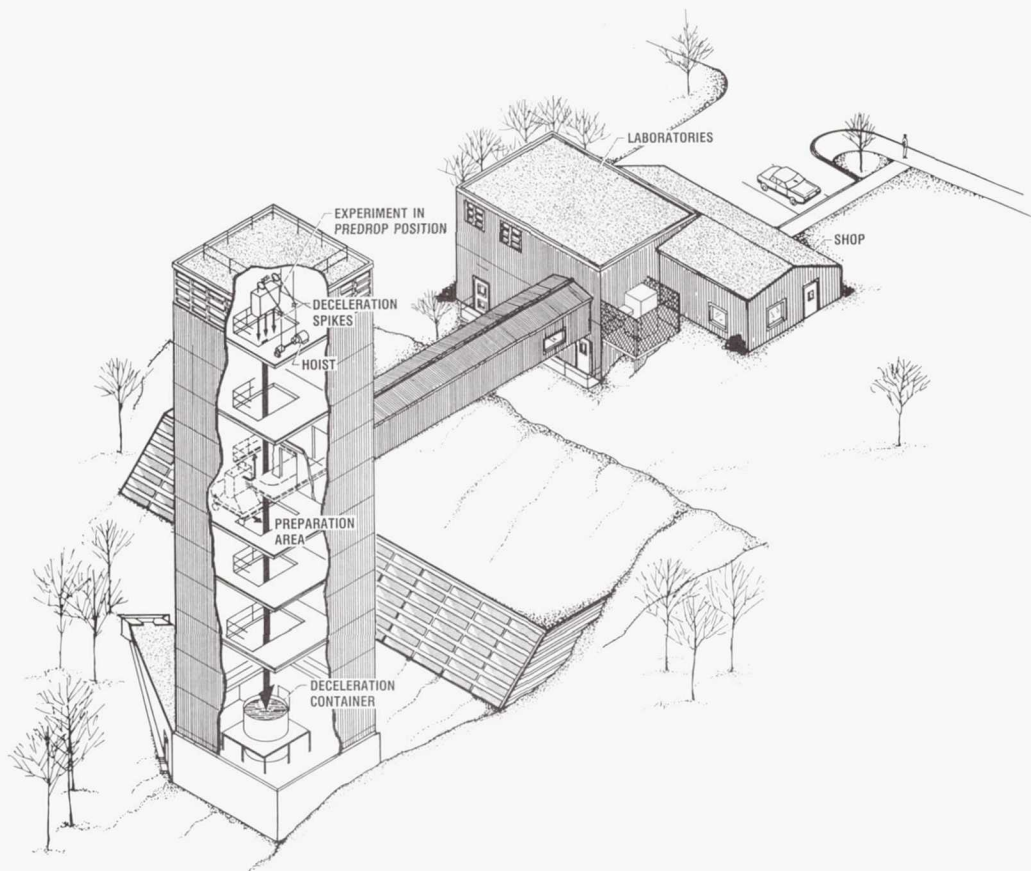
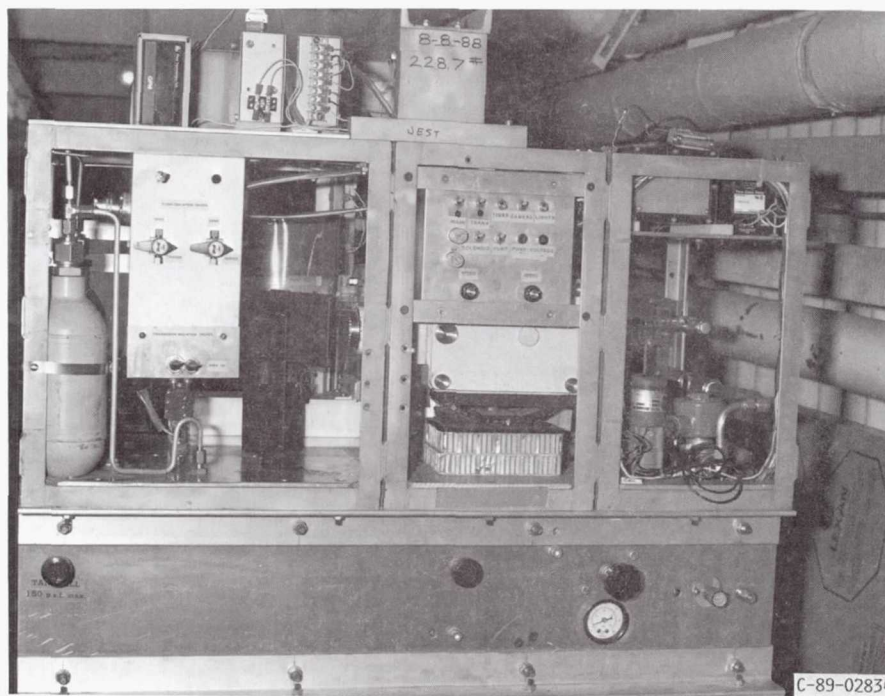


FIGURE 1. - CHARACTERISTIC TIMES AND ACCELERATION LEVELS OF MICROGRAVITY LABORATORY FACILITIES.



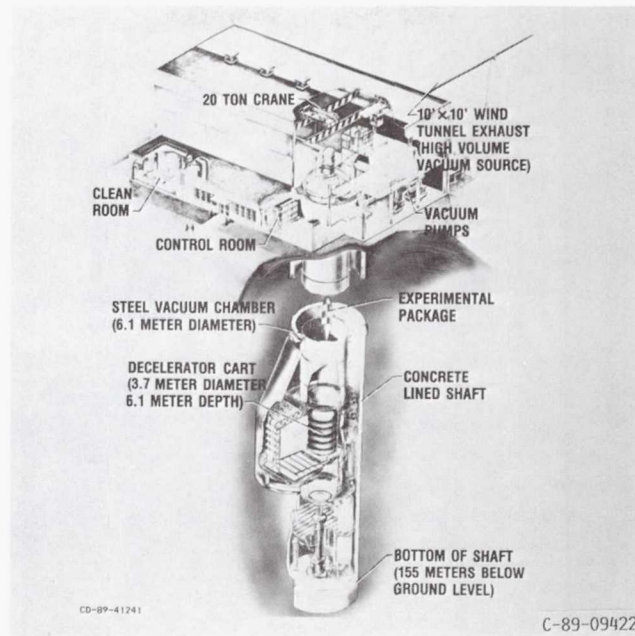
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(a) FACILITY.

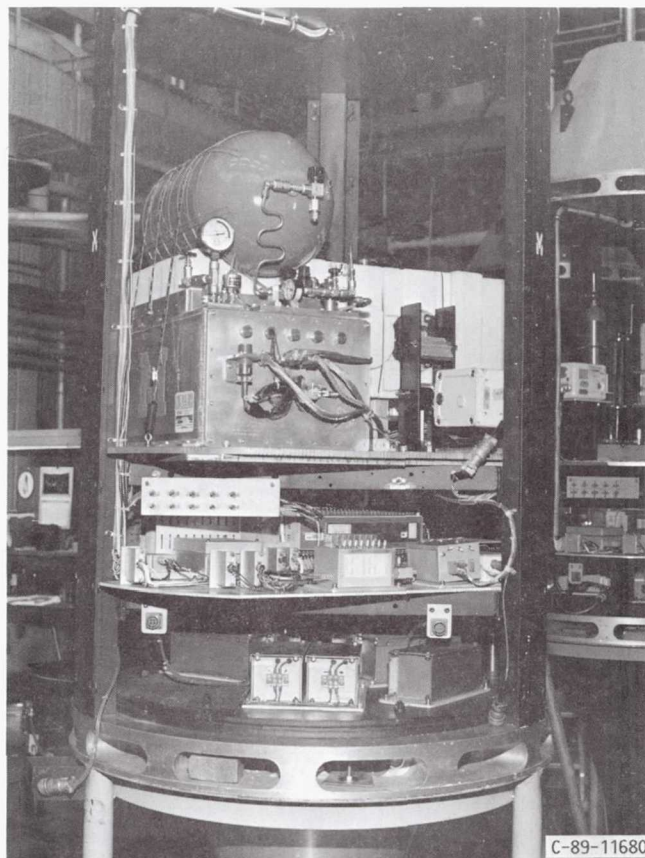


(b) EXPERIMENT PACKAGE (TWO-PHASE FLOWTHROUGH FITTINGS).

FIGURE 2. - NASA LEWIS 2.2-SECOND DROP TOWER.

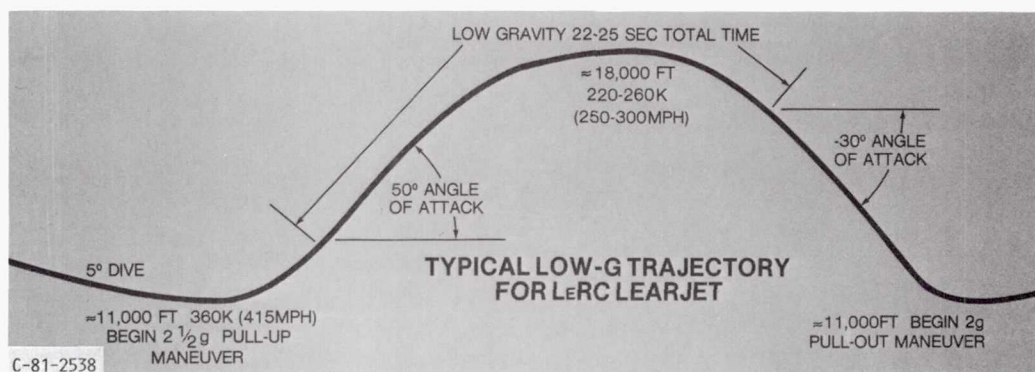


(a) FACILITY.



(b) EXPERIMENT PACKAGE (POOL BOILING EXPERIMENT).

FIGURE 3. - NASA LEWIS ZERO-GRAVITY FACILITY.



(a) MODEL 25 LEARJET AND TYPICAL LOW-g TRAJECTORY.



(b) EXPERIMENT PACKAGE (ADIABATIC TWO-PHASE FLOW).

FIGURE 4. - LEWIS AIRBORNE LOW-GRAVITY FACILITY.

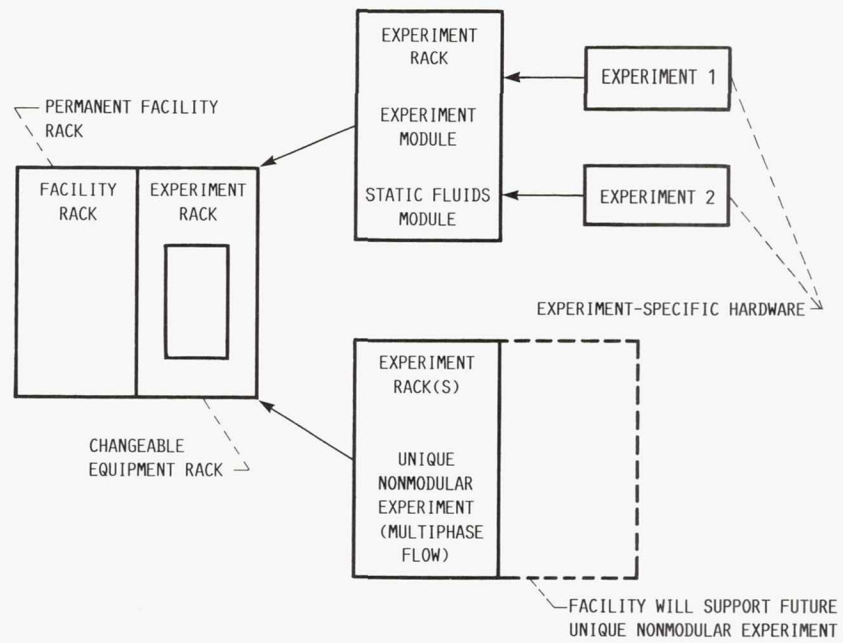


FIGURE 5. - MODULAR CONCEPT FOR FLUID PHYSICS/DYNAMICS FACILITY (FP/DF).

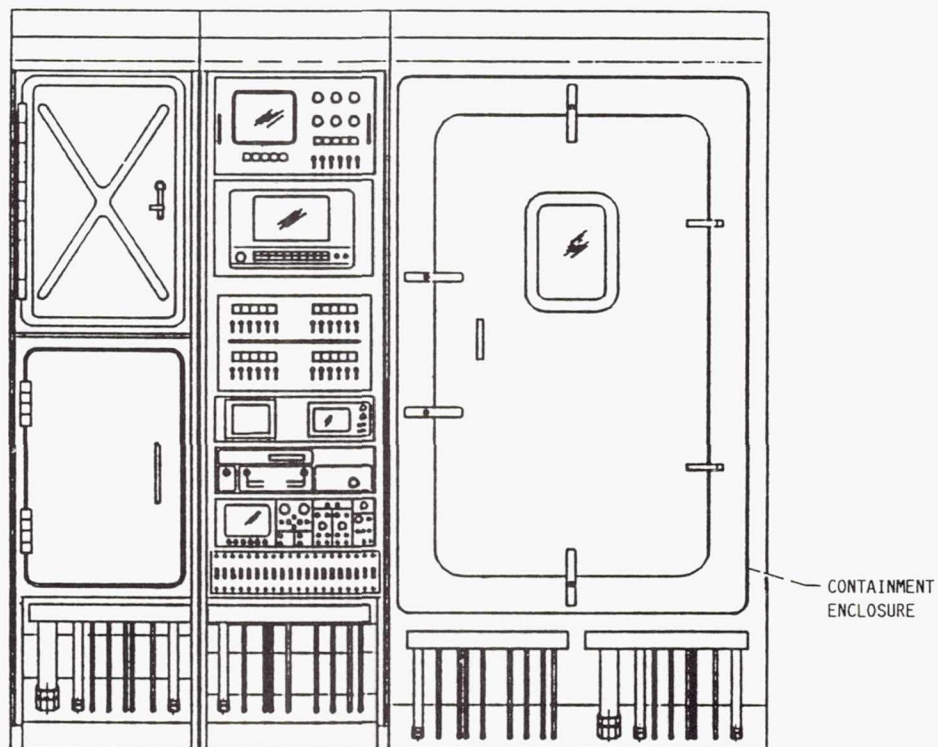
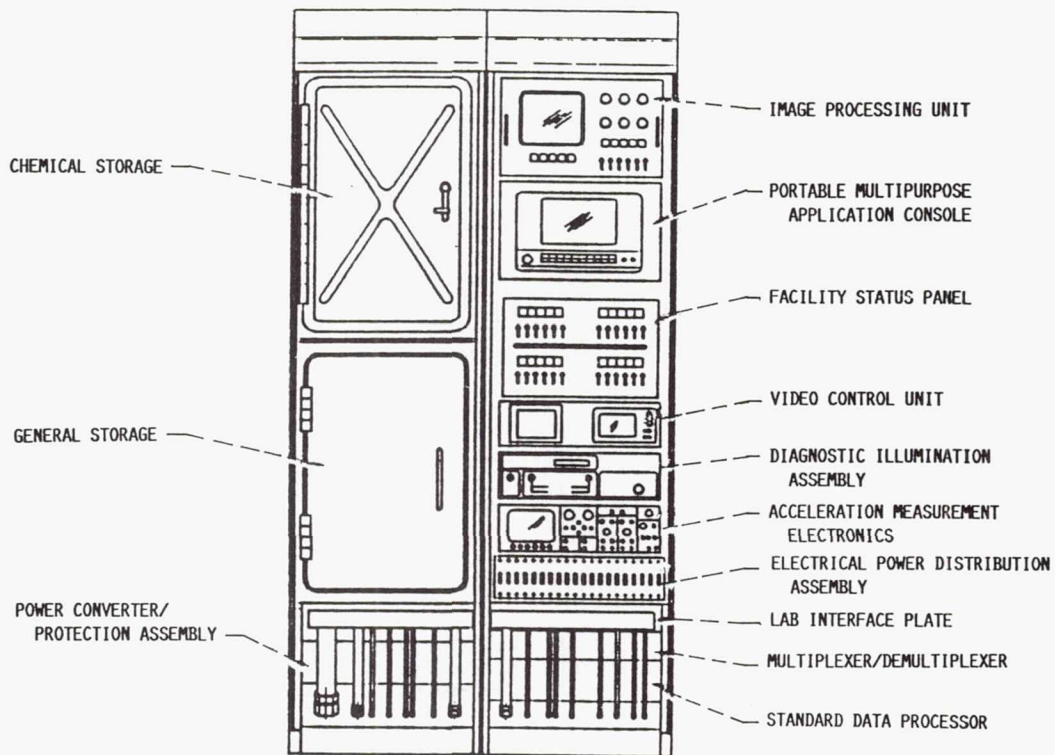
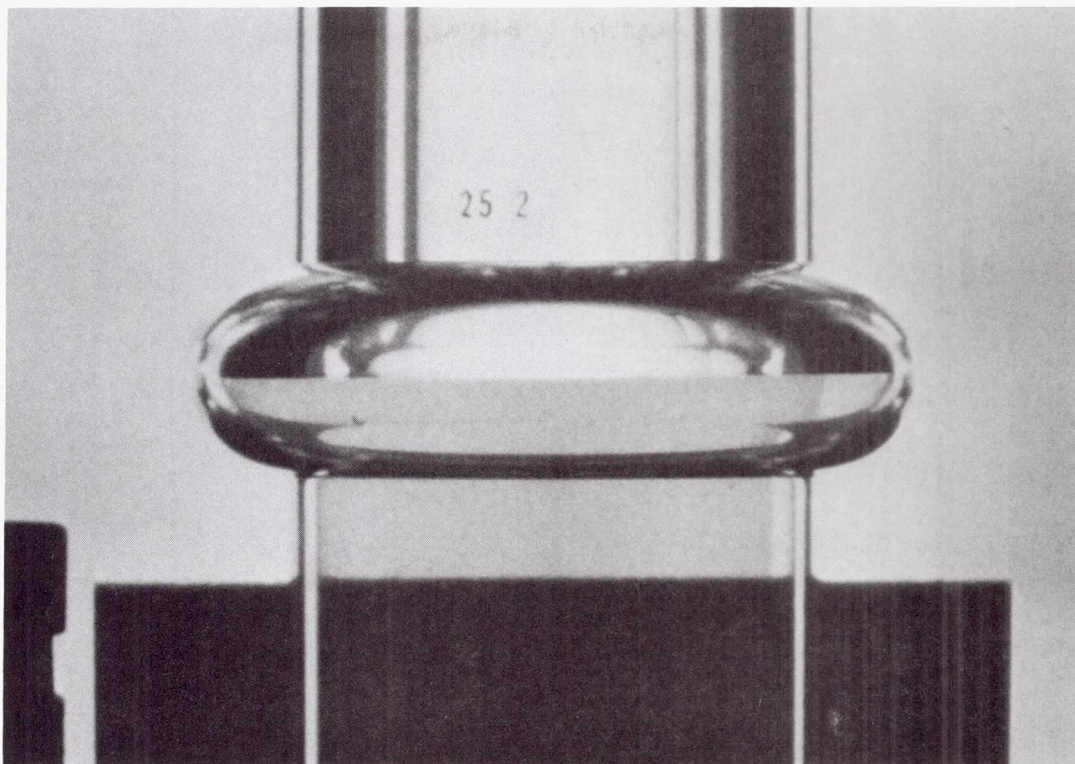
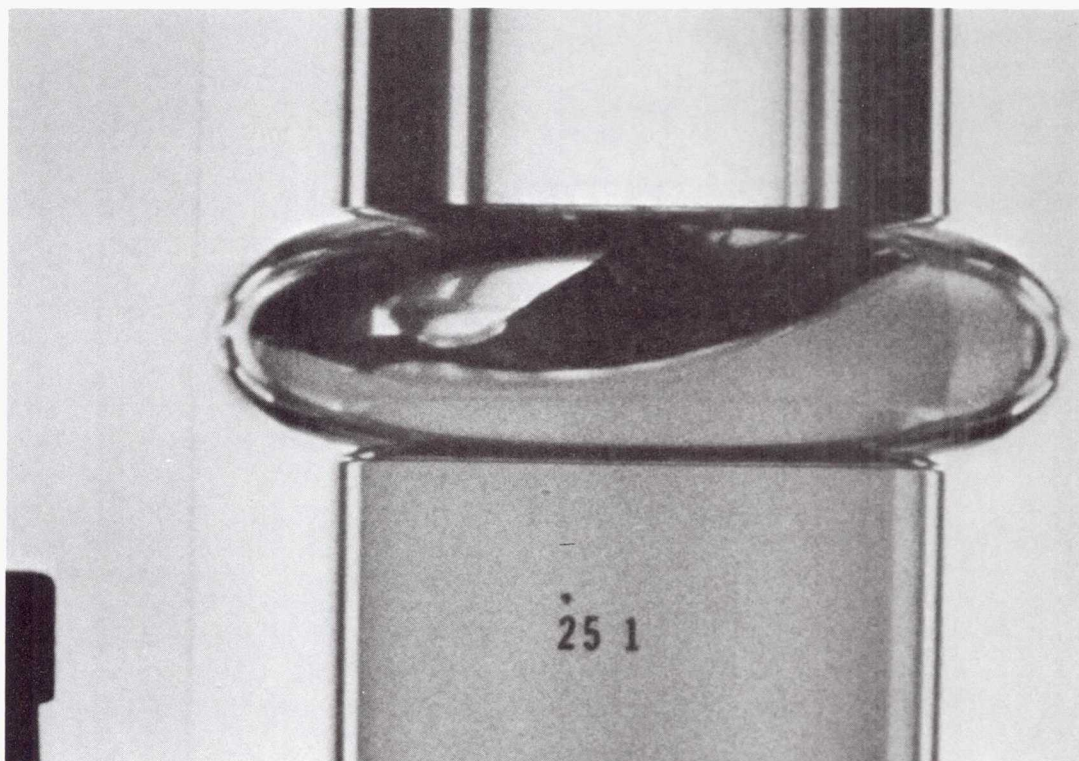


FIGURE 6. - FLUID PHYSICS/DYNAMICS FACILITY (FP/DF).



(a) SYMMETRIC INTERFACIAL CONFIGURATION.



(b) ASYMMETRIC INTERFACIAL CONFIGURATION.

FIGURE 7. - UNIQUE TEST CELL FOR STUDY OF GAS-LIQUID CONFIGURATIONS IN ZERO-GRAVITY FACILITY.

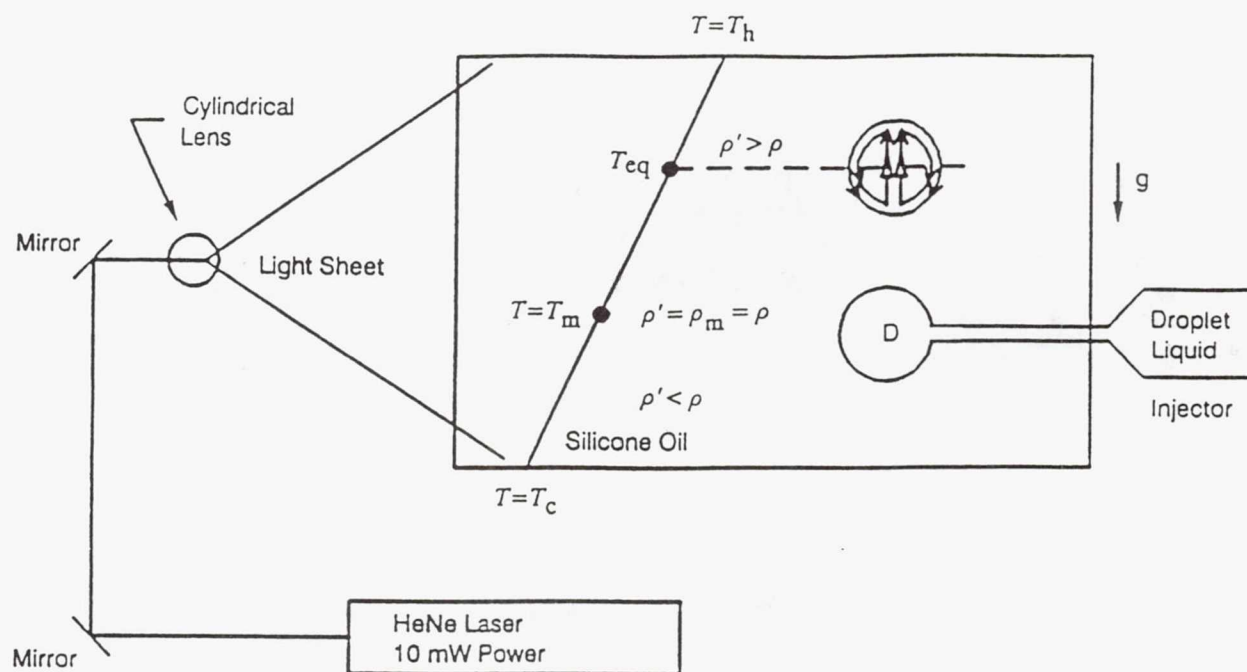


FIGURE 8. - IMMERSED DROPLET, MATCHED-DENSITY, THERMOCAPILLARY EXPERIMENT (T_h IS HOT-SIDE SURFACE TEMPERATURE, T_c IS COLD-SIDE SURFACE TEMPERATURE, T_m IS TEMPERATURE AT MATCHED-DENSITY POSITION, ρ IS DENSITY OF FLUID MEDIUM, ρ' IS DENSITY OF FLUID DROPLET, AND ρ_m IS DENSITY AT MATCHED-DENSITY POSITION).

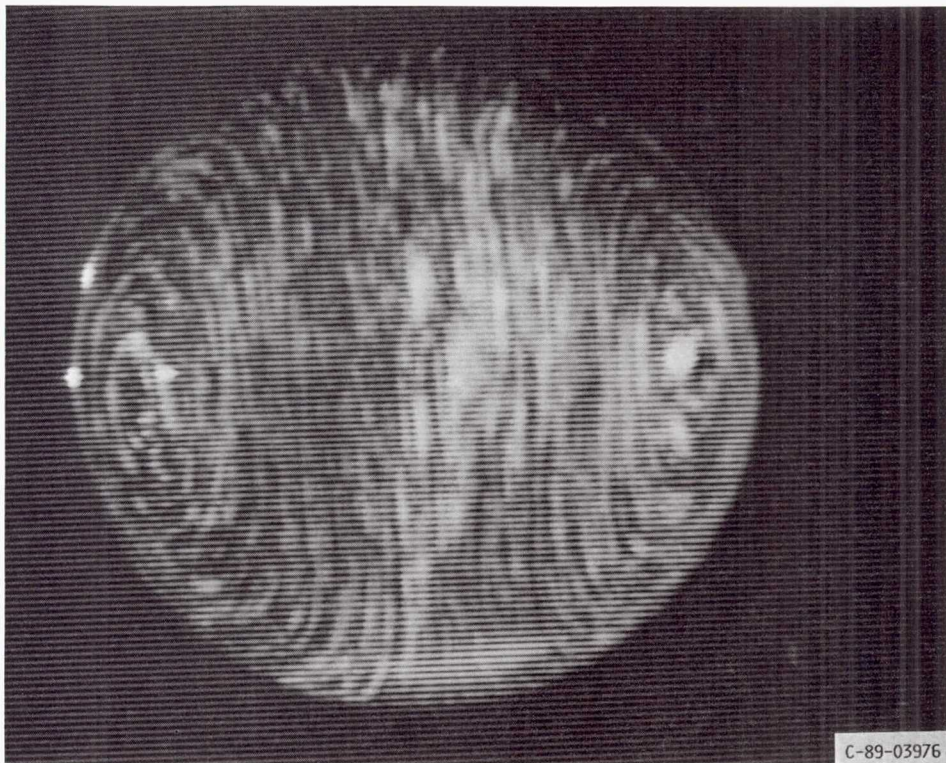


FIGURE 9. - NORMAL-GRAVITY THERMOCAPILLARY FLOW INSIDE A LIQUID DROP IMMERSED IN SILICONE OIL (9-MM-DIAM DROPLET WITH $6^{\circ}\text{C}/\text{cm}$ TEMPERATURE GRADIENT).

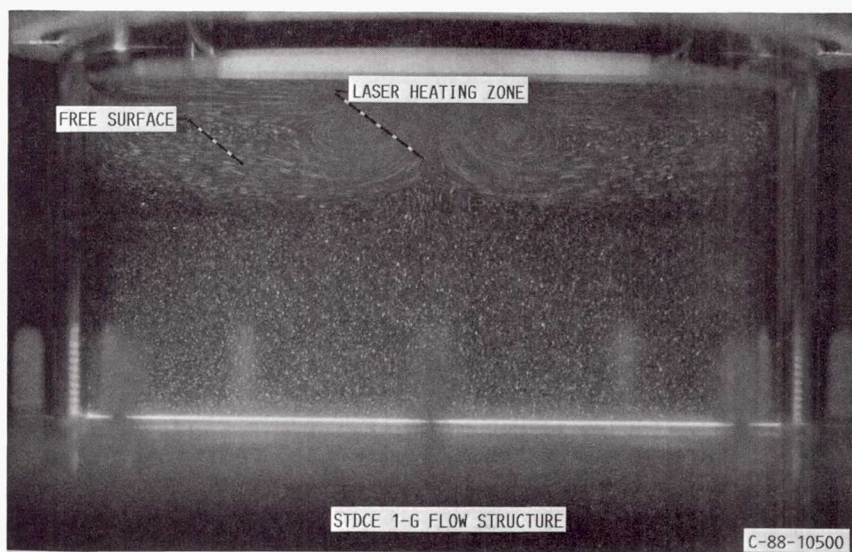


FIGURE 10. - NORMAL-GRAVITY THERMOCAPILLARY FLOW IN CONTAINER OF SILICONE OIL (SURFACE HEATED FROM ABOVE).

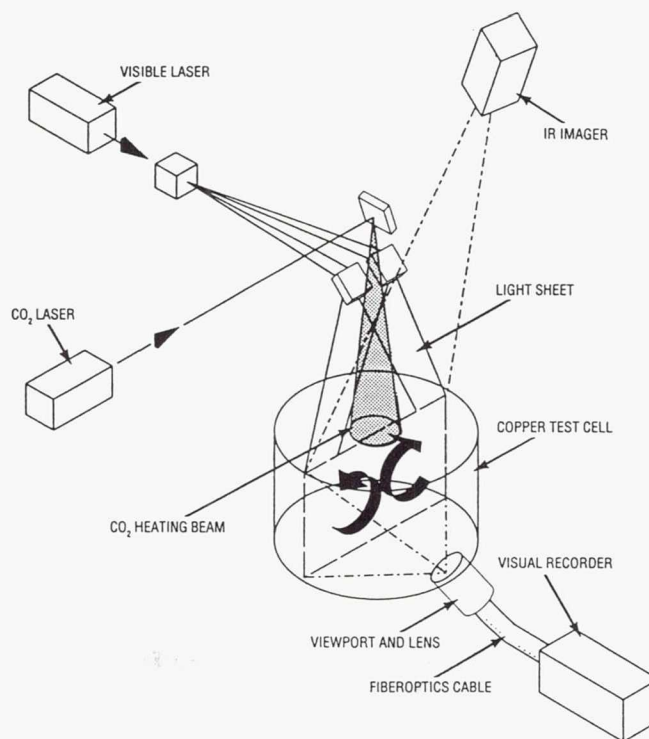
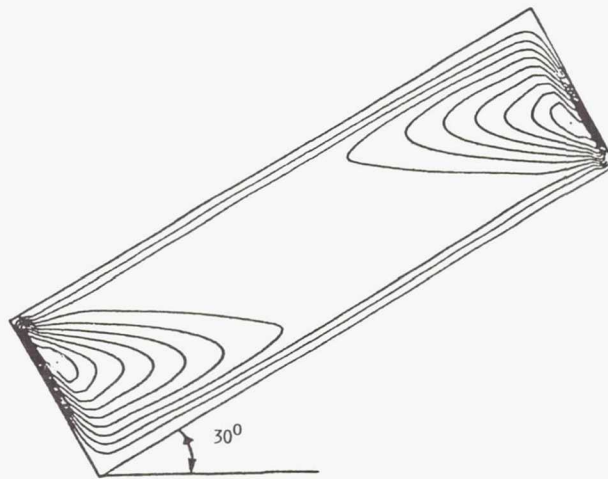
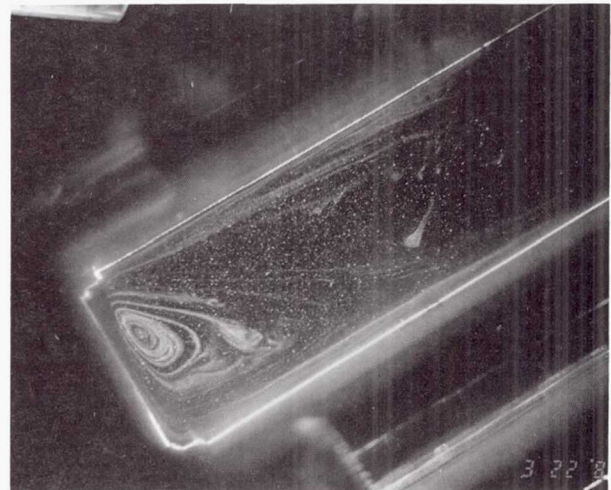
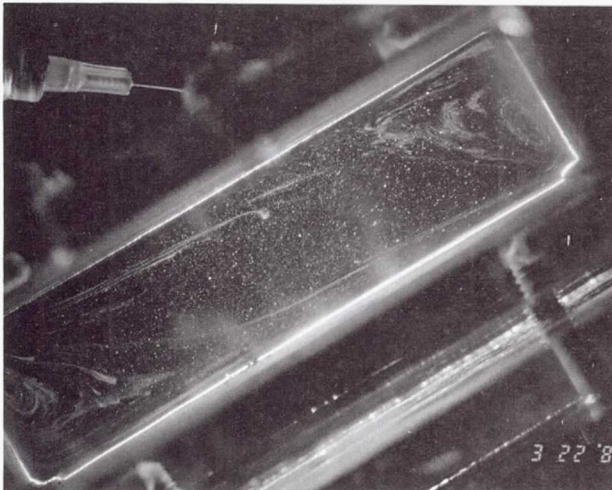


FIGURE 11. - SURFACE-TENSION-DRIVEN CONVECTION EXPERIMENT.

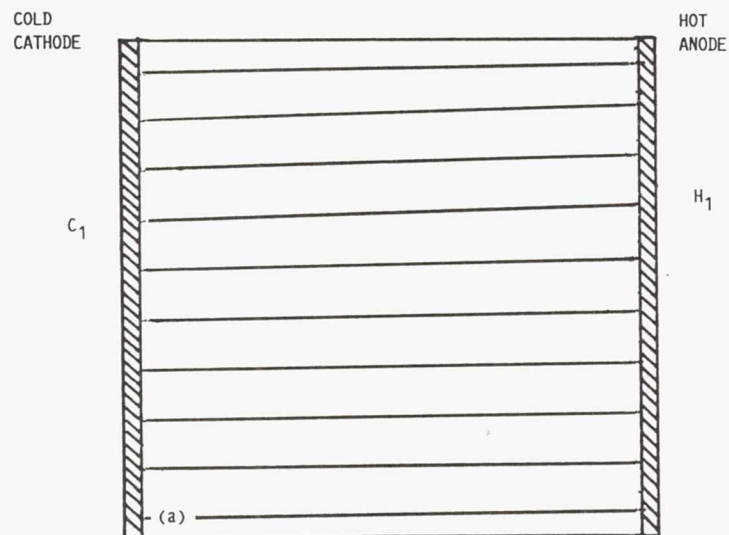


(a) NUMERICAL RESULTS.

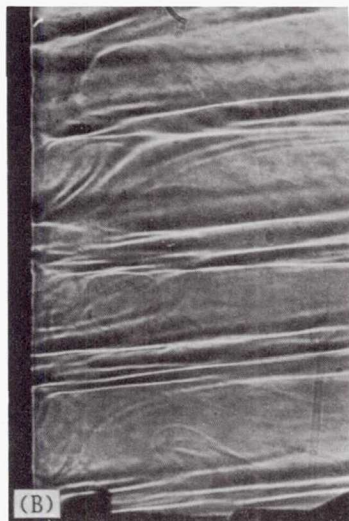


(b) EXPERIMENTS.

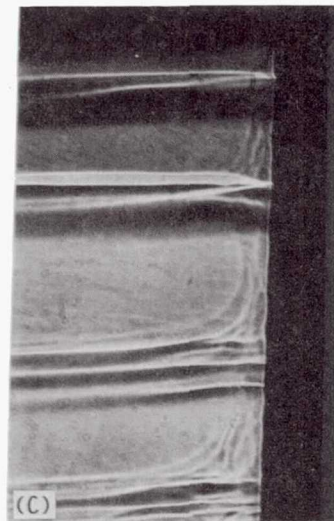
FIGURE 12. - THERMAL CONVECTION FLOW PATTERNS IN ENCLOSURES TILTED AT 30° (RAYLEIGH NUMBER Ra , 2.2×10^6 ; PRANDTL NUMBER Pr , 7; ASPECT RATIO, 0.28).



COLD
CATHODE

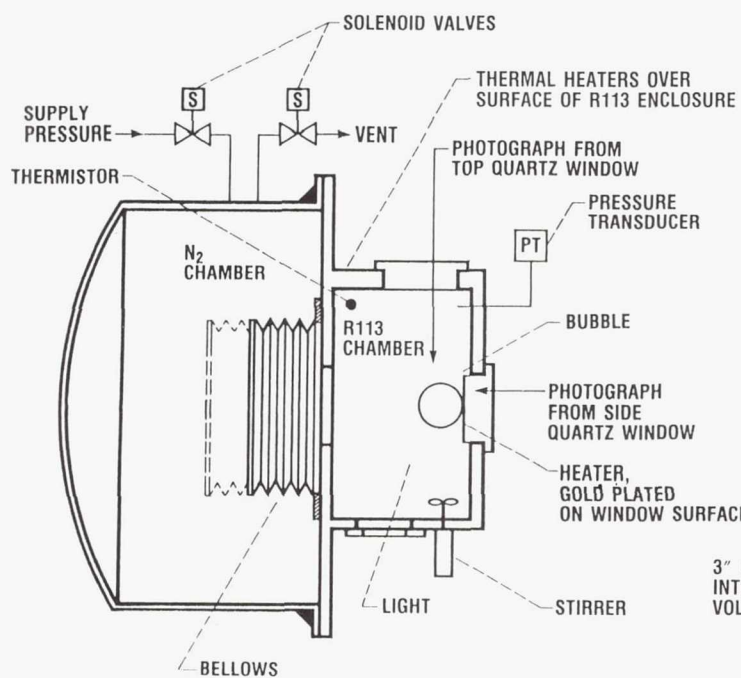


HOT
ANODE

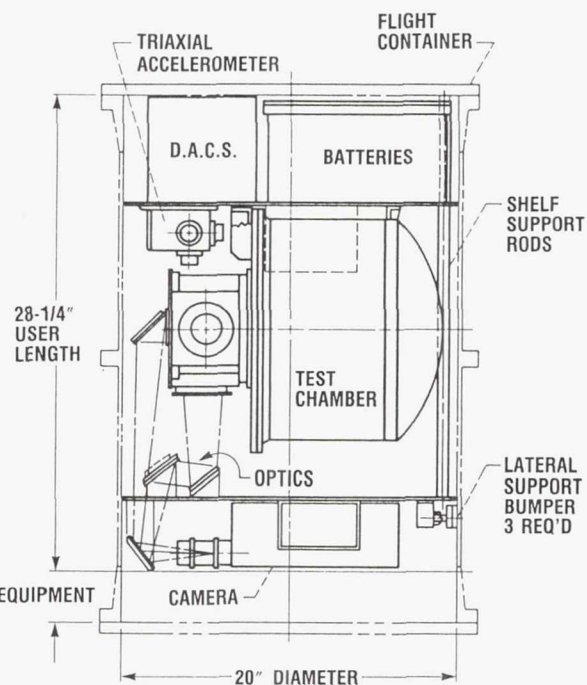


- (a) SERIES OF LAYERS IN FLOW.
- (b) LEFT SIDE OF TEST CELL.
- (c) RIGHT SIDE OF TEST CELL.

FIGURE 13. - THERMAL/SOLUTAL CONVECTION FLOW PATTERNS IN ENCLOSURE ($Ra \times Pr = 2.5 \times 10^6$; ASPECT RATIO, 0.96).



(a) TEST CHAMBER.



(b) SETUP OF EXPERIMENT IN CONTAINER.

FIGURE 14. - POOL BOILING EXPERIMENT.

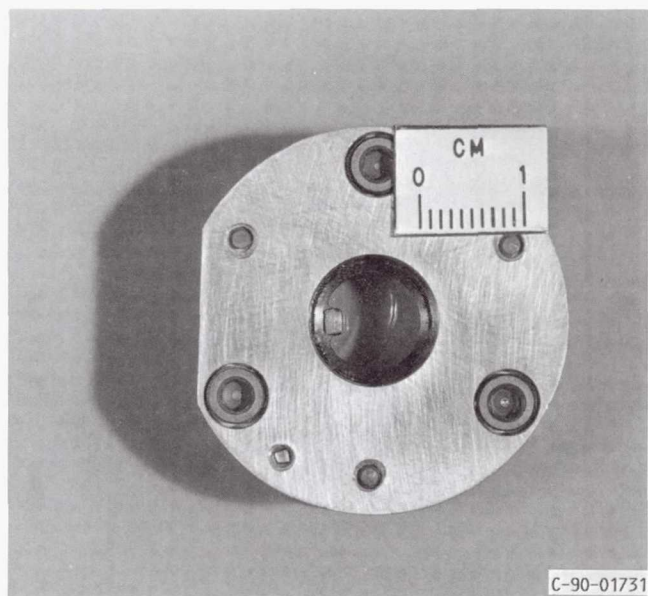


FIGURE 15. - TEST CHAMBER FOR CRITICAL FLUID THERMAL EQUILIBRATION EXPERIMENT.

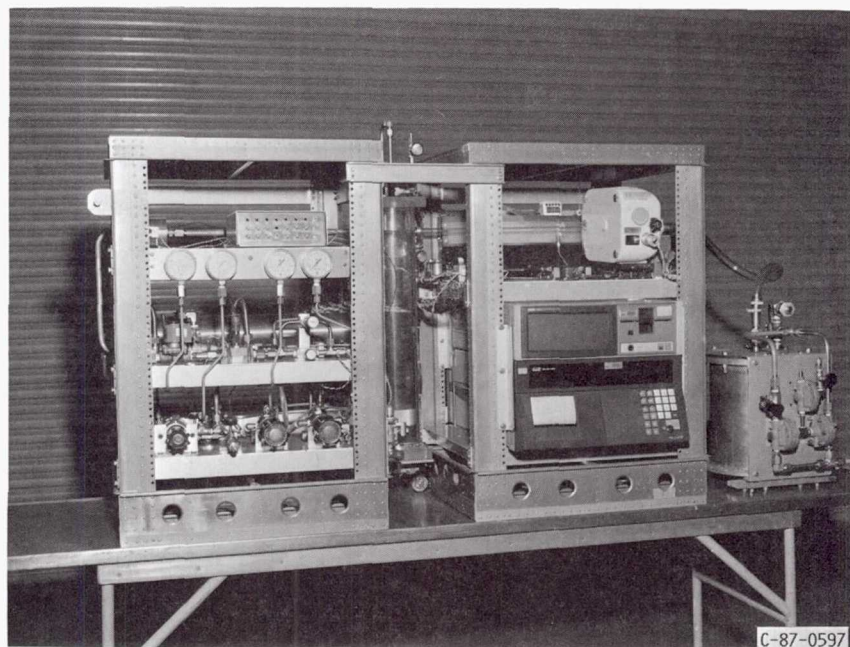


FIGURE 16. - EXPERIMENTAL PACKAGE FOR ADIABATIC TWO-PHASE FLOW EXPERIMENT (LEARJET FACILITY).

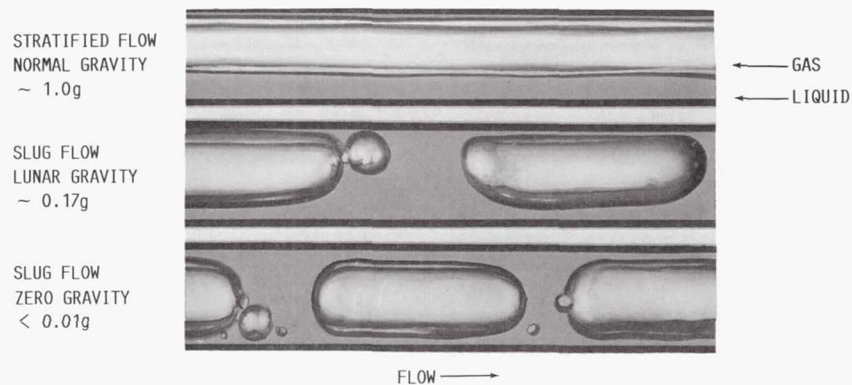


FIGURE 17. - TWO-PHASE FLOW REGIMES DEMONSTRATING EFFECT OF DIFFERENT GRAVITY LEVELS (LEARJET FACILITY; AIR/WATER IN 1.27-CM-i.d. TUBE; SUPERFICIAL GAS VELOCITY, ~ 0.14 M/SEC; SUPERFICIAL LIQUID VELOCITY, ~ 0.07 M/SEC).

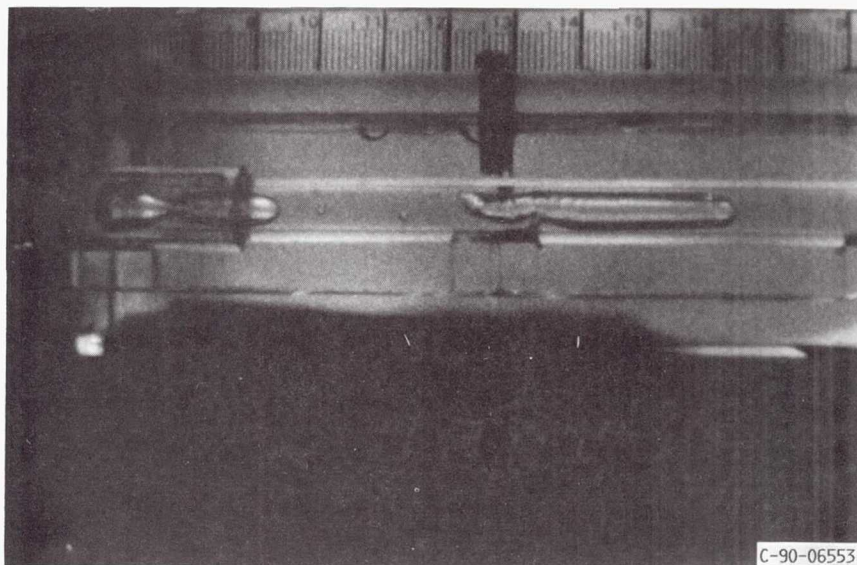


FIGURE 18. - TAYLOR BUBBLES ENTERING CONTRACTION IN LOW GRAVITY (DROP TOWER FACILITY).

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16. Abstract This document presents an overview of the microgravity fluid physics program at Lewis Research Center. This program is sponsored by the Office of Space Science and Applications (OSSA) at NASA Headquarters and is part of a broader science program at OSSA to study fundamental sciences, materials sciences, and biotechnology. This report focuses on fundamental fluid physics in the hope of stimulating investigations into new areas of microgravity research. One of the main reasons for conducting low-gravity research in fluid physics is to study phenomena such as surface tension, interfacial contact angles, and diffusion independent of such gravitationally induced effects as buoyant convection. Fluid physics is at the heart of many space-based technologies including power systems, thermal control systems, and life support systems. Fundamental understanding of fluid physics is a key ingredient to successful space systems design. In addition to describing ground-based and space-based low-gravity facilities, this report presents selected experiments which highlight Lewis work in fluid physics. These experiments can be categorized into five theme areas which summarize the work being conducted at Lewis for OSSA: (1) isothermal/iso-solutal capillary phenomena, (2) capillary phenomena with thermal/solutal gradients, (3) thermal-solutal convection, (4) first- and second-order phase transitions in a static fluid, and (5) multiphase flow.					
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